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Behavior of Laboratory-Made Spray Ice in Triaxial Compression Testing

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Abstract: The increasing use of spray ice in arctic offshore exploration and construction initiated a study that includes a series of triaxial compression tests on saline, laboratory-made spray ice. Factors affecting spray-ice behavior and its engineering properties are independently selected and assessed, and the results are compared with the existing literature on spray ice and similar materials. The stress-strain behavior of spray ice is studied for isotropic consolidation pressures ranging from 45 to 172 kPa, applied for four to 19 hours. The constant rates of strain used during the triaxial compression are 1.5×10^{-6} s^{-1} and 1.8×10^{-5} s^{-1}. The test temperature is $-10°$ C with a few tests performed at $-5°$ C. For the range of strain rates considered, a yield strength envelope for spray ice is suggested that separates the initial quasi-elastic behavior from plastic deformations; beyond the yield surface, the material behaves as a frictional medium. The results compare well with previous published analysis, despite the limited number of tests.

Introduction

The high cost of construction in the Arctic and the need for temporary structures in offshore oil exploration have made spray ice an attractive material for artificial islands, access roads, bridges, or drilling pads (Kemp 1984; Duthweiler et al. 1985; Goff et al. 1986; Juvkam-Wold 1986; Masterson et al. 1986; Funegard et al. 1987). Spray ice is a fine granular material obtained by the high-pressure spraying of water into cold air. Field production techniques have improved over the last decade (Jahns et al. 1986; Goff et al. 1986), and spray-ice technology has advanced enough to compete economically with other design alternatives. Of particular advantage are the local availability of the material (fresh or sea water) and the environmental safety of these temporary structures.

Since spray ice is a relatively new material, only a limited amount of laboratory tests has been reported in the literature (Prodanovic 1986; Weaver et al. 1986). Knowledge of the shear strength and failure processes of spray ice is therefore required to provide design parameters for the ice structures. In addition, further research was thought necessary to increase spray-ice production capacities while maintaining a competent material. In situ testing with the pressuremeter, laboratory production, and triaxial testing have been combined to achieve these goals (Steel 1989).

The purpose of this paper is to present the results from a series of triaxial compression tests under lateral confining pressure that has been carried out on laboratory-made spray ice. The results reveal the effect of the following

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parameters on spray-ice behavior: isotropic consolidation pressure and consolidation time, confining pressure during shear, rate of deformation, and temperature.

The test results have been interpreted according to existing behavior models and compared to similar results obtained for materials like broken ice (Keinonen and Nyman 1978; Gale et al. 1987; Wong et al. 1988) and to the limited existing test results on spray ice (Weaver et al. 1986; Prodanovic 1986).

Laboratory Production of Spray-Ice and Sample Preparation

For the laboratory production of spray ice, it was necessary to obtain a reasonable quantity of material with each spraying, showing similar properties as the material in the Arctic. Repeatability of the physical properties of the produced spray ice was also important. The material used in these experiments was obtained by spraying saline water through a nozzle with compressed air into a cold room initially set at -20 to $-25°$ C. The cold room and test facilities were located at the Engineering Building of Memorial University, St. John's, Newfoundland, Canada. The spray nozzle was placed in a port on the back wall of the cold room, and compressed air and water were fed to the nozzle from outside the room.

The spray ice produced was a damp-to-wet granular material. The ice grains were well sorted as typically shown in Table 1 and approximately 1 mm in diameter. During the preparation period, some brine drainage, sintering, and grain growth occurred. In order to have consistent sample characteristics, the spray ice was gently broken up by hand prior to specimen preparation. The salinity of the ice was also checked to ensure relative uniformity between the specimens.

The triaxial samples were made of spray ice that was sieved through a 1.68-mm mesh (#12 U.S. sieve). The spray ice was placed in a 77-mm-diameter triaxial mold lined with a thin rubber membrane, similar to that used for sand samples (Bishop and Henkel 1962). The material was pluviated and compacted in five lifts with a wooden cylinder. The initial bulk density was approximately 650 kg/m^3. The diameter, height, and weight of the sample were measured both before and after testing.

Test Equipment

The spray-ice samples were tested in a standard, commercially available triaxial cell, modified to incorporate cooling coils. An antifreeze liquid was

TABLE 1. Grain Size of Laboratory-Made Spray Ice

Sieve number (1)	Mesh size (mm) (2)	Percentage passing in weight (3)
U.S. #10	2.00	100
U.S. #16	1.18	85
U.S. #20	0.85	35
U.S. #30	0.60	10

TABLE 2. Review of Selected Test Parameters

Test set number (1)	Number of samples (2)	Temperature (°C) (3)	Consolidation pressure (kPa) (4)	Shear Strain	
				Time (hr) (5)	Rate (s^{-1}) (6)
I (Reference)	4	−10	86	4	1.5×10^{-4}
II	3	−10	45*	4	1.5×10^{-4}
III	3	−10	172*	4	1.5×10^{-4}
IV	2	−10	86	19*	1.5×10^{-4}
V	4	−10	86	4	1.8×10^{-5a}
VI	2	−10	45*	19*	1.5×10^{-4}
VII	3	−10	172*	19*	1.5×10^{-4}
VIII	2	−5*	86	4	1.5×10^{-4}

*This parameter differs from the reference set.

TABLE 3. Initial Properties and Test Data

Sample number (1)	Initial density (kg/m^3) (2)	Salinity at 20° C (‰) (3)	Temperature (°C) (4)	Consolidation pressure (kPa) (5)	Consolidation time (hr) (6)	Rate of axial shear strain (s^{-1}) (7)
I-1	0.574	—	−10	86.2	4.17	1.49×10^{-4}
I-2	0.597	—	−10	86.2	4.10	1.51×10^{-4}
I-3	0.592	—	−10	86.2	4.00	1.45×10^{-4}
I-4	0.639	8.5	−10	86.2	3.93	1.47×10^{-4}
II-1	0.550	8.0	−10	44.8	4.00	1.23×10^{-4}
II-2	0.636	10.3	−10	44.8	4.00	1.48×10^{-4}
II-3	0.627	—	−10	44.8	4.03	1.50×10^{-4}
III-1	0.678	9.3	−10	172.4	4.00	1.40×10^{-4}
III-2	0.638	—	−10	172.4	4.05	1.44×10^{-4}
III-3	0.654	—	−10	172.4	3.97	1.48×10^{-4}
IV-1	0.652	—	−10	79.3	19.03	1.53×10^{-4}
IV-2	0.656	11.7	−10	86.2	18.20	1.40×10^{-4}
V-1	0.731	8.5	−10	86.2	4.00	1.78×10^{-5}
V-2	0.687	9.2	−10	86.2	4.25	1.72×10^{-5}
V-3	0.697	10.0	−10	86.2	4.00	1.79×10^{-5}
V-4	0.610	6.8	−10	82.7	4.12	1.82×10^{-5}
VI-1	0.627	9.7	−10	44.8	17.66	1.42×10^{-4}
VI-2	0.659	11.5	−10	44.8	18.05	1.40×10^{-4}
VII-1	0.684	14.0	−10	172.4	17.92	1.46×10^{-4}
VII-2	0.638	15.7	−10	172.4	19.83	1.47×10^{-4}
VII-3	0.643	7.5	−10	172.4	18.50	1.72×10^{-4}
VIII-1	0.638	9.5	−5	82.7	4.00	1.47×10^{-4}
VIII-2	0.633	8.2	−5	82.7	4.00	1.46×10^{-4}

TABLE 4. Triaxial Test Results

Sample number (1)	Computed consolidation strain (%) (2)	Yield strength $(\sigma_1 - \sigma_3)/2$ (kPa) (3)	Strength at 20% deformation (kPa) (4)	Rate of strain hardening (kPa/%) (5)
I-1	9.6	130	210	7.9
I-2	5.4	110	230	13.3
I-3	9.6	115	158	3.5
I-4	2.7	160	225	4.4
II-1	5.4	100	83	NA[a]
II-2	1.5	120	70	NA
II-3	2.7	130	63	NA
III-1	7.5	230	355	9.9
III-2	6.3	205	320	11.3
III-3	7.5	230	355	9.9
IV-1	3.6	268	275	1.2
IV-2	3.3	230	258	1.2
V-1	5.4	160	240	5.4
V-2	3.3	80	240	14.3
V-3	3.6	83	240	13.8
V-4	3.3	65	200	12.8
VI-1	3.9	160	162	NA
VI-2	3.0	185	150	NA
VII-1	9.6	338	440	7.4
VII-2	9.6	268	315	3.7
VII-3	11.1	340	475	14.8
VIII-1	4.5	138	238	5.9
VIII-2	5.7	138	225	6.9

[a]NA = not applicable (strain softening).

circulated in the coils. The temperature of the liquid was kept constant, within 0.1° C, by a bath that incorporated a heating and cooling unit. The cold-room temperature was kept within 2° C of the test temperature.

The axial compression load (in the major principal stress direction) was applied by a motorized load frame with a predetermined constant rate of displacement. The load was measured by an electronic transducer external to the triaxial cell (sensitivity of 10 N).

The axial deformation of the sample was recorded by an external electronic transducer (sensitivity of 0.05 mm). It indicated that the actual rate of strain was uniform throughout the test and close to the predetermined value.

The lateral confining pressure (in the minor principal stress direction) was kept constant during the isotropic consolidation and subsequent axial

compression. It was controlled by an air pressure regulator to a precision of 0.1 kPa. The use of air as the cell fluid, although very simple to operate, prevented direct measurement of sample volume changes during the tests.

The top and bottom end plates were made of well-polished stainless steel.

Testing Program and Results

The testing program is summarized in Table 2. The reference set of samples was tested at $-10°$ C, after four hours of isotropic consolidation under a cell pressure of 86 kPa. These samples were sheared at an axial strain rate of $1.5 \times 10^{-4}\ s^{-1}$. The other sets of tests differ from the reference by changing one or two of the four parameters as shown in Table 2.

The results of the tests are presented in Tables 3 and 4 and shown in Figs. 1–5. The axial deviatoric stress has been computed using a corrected area

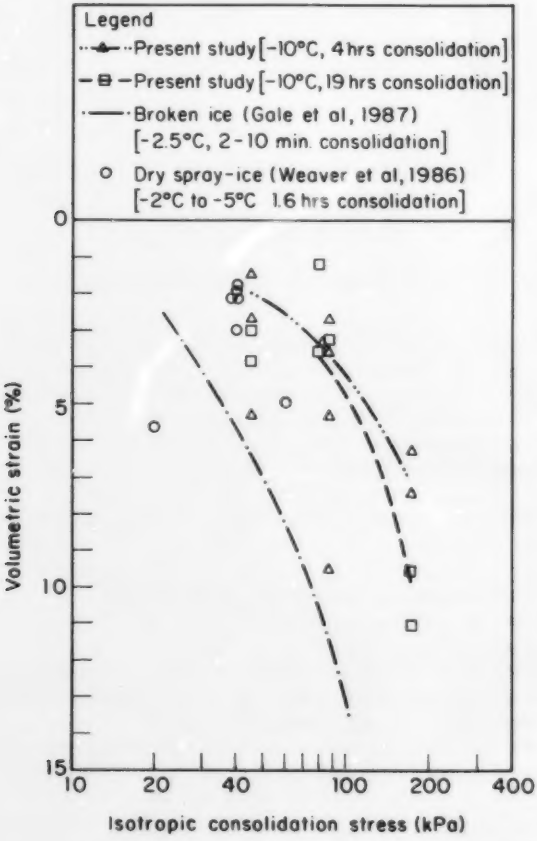

FIG. 1. Isotropic Consolidation Properties

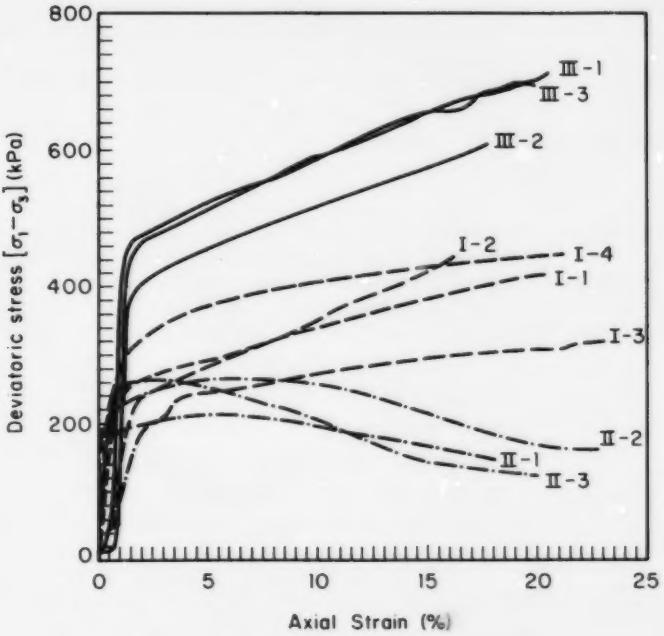

FIG. 2. Shear Test Results (Sets I, II, and III)

with the assumption that the sample remains cylindrical during shear. This can lead to a slight overestimation of the stress for cases where the specimen exhibited a barrel shape at large deformations. The axial strain is defined hereafter as the ratio of the axial deformation to the initial height of the sample. The volumetric isotropic consolidation strain shown in Table 4 and Fig. 1 is computed from the axial strain monitored during the isotropic consolidation.

The results are separated into two stages: the consolidation phase and the shear phase.

Isotropic Volume Changes during Consolidation

The values of the volumetric consolidation strain listed in Table 4 are plotted against the logarithm of the applied isotropic pressure after consolidation durations of four hours and 19 hours (Fig. 1). The average isotropic compression curves obtained are parallel to the curves presented by Gale et al. (1987) for broken ice. Generally, the longer consolidation time and higher isotropic pressure translate into an increased volumetric strain. These results are also consistent with the data by Weaver et al. (1986) on dry spray ice.

Stress-Strain Behavior during Triaxial Compression

Fig. 2 shows three typical behaviors of spray ice under increasing confining pressure. Initial conditions were the same: relatively short consoli-

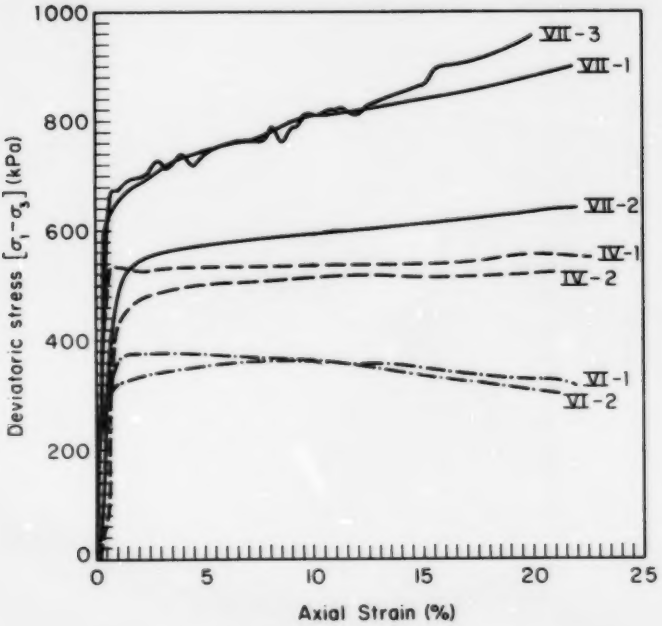

FIG. 3. Shear Test Results (Sets IV, VI, and VII)

dation time (four hours), low temperature (−10° C), and high rate of shear (1.5×10^{-4} s^{-1} or approximately 20% deformation in 25 min). At low confining pressures (45 kPa, set II), the stress-strain curves indicate a low initial modulus and a peak value followed by strain softening. At medium confining pressure (86 kPa, set I), no peak stress occurs, even at large strains. Instead, after an inflection point (yield strength) the deviatoric stress increases slightly and uniformly (strain hardening). At higher confining pressures (172 kPa, set III), the bilinear shape is more pronounced and the rate of strain hardening increases.

Visual observations made after testing indicated that, for low confining pressure, the samples generally exhibited large heterogeneous shear zones in the middle third of the height. When strain hardening occurred (at higher confining pressures), the samples showed uniform bulging. The heterogeneous deformations and the corresponding softening observed at low confining pressure may be partially caused by end effects. However, there was no evidence of rigid end edges, and it is generally admitted that a ratio of length over diameter of 2 ensures a relatively uniform stress distribution in the middle third of the specimen. The heterogeneous deformations must therefore be related to failure along weaker zones in the material. These zones seem to disappear for higher confining pressures, probably due to more even contact pressures between spray-ice grains.

Fig. 3 shows similar tests on samples where the consolidation pressure

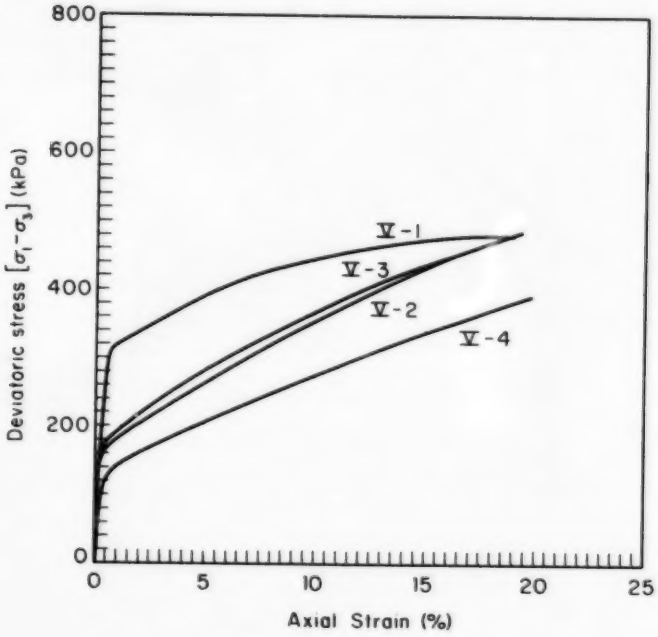

FIG. 4. Shear Test Results (Set V)

was sustained over a 19-hour period. The same typical shapes are observed with the exception of the peak-softening behavior, at the low confining pressure, which was not as pronounced as it was for the short consolidation time.

In general, it was found that the higher confining pressures and longer consolidation times resulted in higher strength values for the samples tested. The initial density is also an important factor; from the results presented here, it appears that a greater initial density leads to a higher value of the yield strength. The method of placement, although shown to be reliable and repeatable, may also induce heterogeneity in the specimen, which increases the scatter of the results.

Comparing set V (Fig. 4) with the reference set I (Fig. 2), it appears that a slower rate of deformation induces a lower yield strength. However, since the rate of strain hardening increases, the value of the strength at large deformations (over 20%) is not significantly affected.

Temperature was initially selected as an important factor affecting the consolidation and shear properties of spray ice. Figs. 1 (set I) and 5 (set VIII) show, surprisingly, that a decrease in temperature from -5 to $-10°$ C has only a slight effect on the stress-strain plots. However, further investigation is needed, in particular for the 0° C to $-5°$ C range of temperature.

Interpretation of Results

The stress-strain plots suggest the existence of a yield-strength envelope separating the initial quasielastic behavior from large, plastic, permanent de-

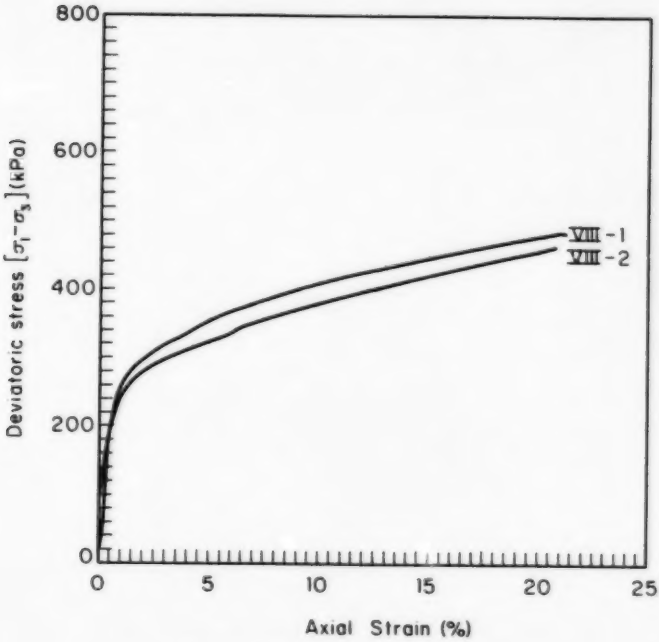

FIG. 5. Shear Test Results (Set VIII)

formations. According to Wong et al. (1989), who observed broken-ice stress-strain plots that were very similar to the present ones, the peak or the point of intersection of the linear portions of the curves can be interpreted as a yield strength in an elasto-plastic model. In the present tests, the rate of strain was high enough to avoid significant visco-plastic deformation (creep) of the individual ice grains during the shear process. Previous studies on comparable solid ice (Shields et al. 1988) indicate less than 1% creep deformation for the same range of strain rates. The yield-strength envelope is therefore primarily associated with the mechanical properties of the assembling of the spray-ice grains rather than the deformation of the individual particles. Using Wong's criterion, the values of the yield strength are listed in Table 4.

The axial deformation beyond the yield envelope can be arbitrarily described using the strength at 20% strain as indicated in Table 4. The strain-hardening rate (slope of the strain-stress curve in the postyield zone) is also computed, when present.

The yield-strength envelope reflects the structure acquired by the assembling of the ice grains during the forming and consolidation of the specimen. Two processes are predominant: the rearrangement and deformation of the assembling of the grains and the modification of contact properties between ice particles, or sintering (Ramseier et al. 1967). The relative influence of these processes is certainly dependent on the stress state and duration im-

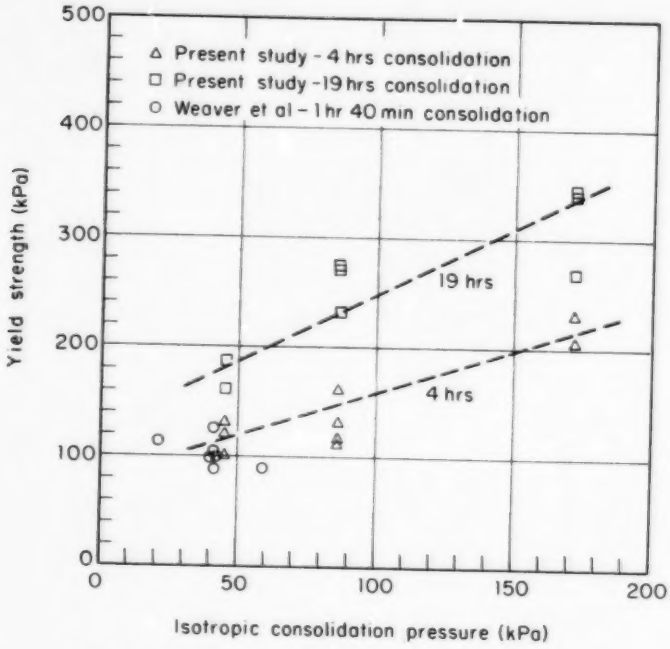

FIG. 6. Influence of Consolidation Time on Yield Strength

posed on the material. The effect of the isotropic consolidation pressure on the yield strength is shown in Fig. 6 for consolidation times of four and 19 hours. Fig. 7 shows the influence of the strain rate on the yield strength of the spray ice. Increasing the shear strain rate leads to a higher yield strength, thus indicating that the yield surface is time-dependent. Although evident, the magnitude of this effect must be confirmed by further experiments.

Beyond the yield surface, the initial structure is erased, the assembling of the grains tends to behave like a cohesionless material, and frictional properties of the ice become predominant. Fig. 8 shows the 20% deformation stress points in a stress-path diagram [$p = (\sigma_1 + \sigma_3)/2$, $q = (\sigma_1 - \sigma_3)/2$], where σ_1 = the vertically applied stress; and σ_3 = the confining pressure. A linear envelope could be drawn through these points with a corresponding internal friction angle of about 49°. Results reported by Weaver et al. (1986) have been recomputed and are shown in Fig. 8. These tests were performed on dry fresh-water spray ice with grain size ranging between 0.4 and 0.63 mm. The average initial density was 550 kg/cm^3. The rate of shear was 6.7 $\times 10^{-5}$ s^{-1} on average, and temperature was about $-2°$ C. The experimental arrangement was very similar to the one used in the present study. The data reported by Weaver et al. (1986) plot slightly above the present study points but show good correlation. The variations in the experimental conditions and test material are likely to explain the slight discrepancy.

The rate of strain hardening is dependent on the confining pressure, among

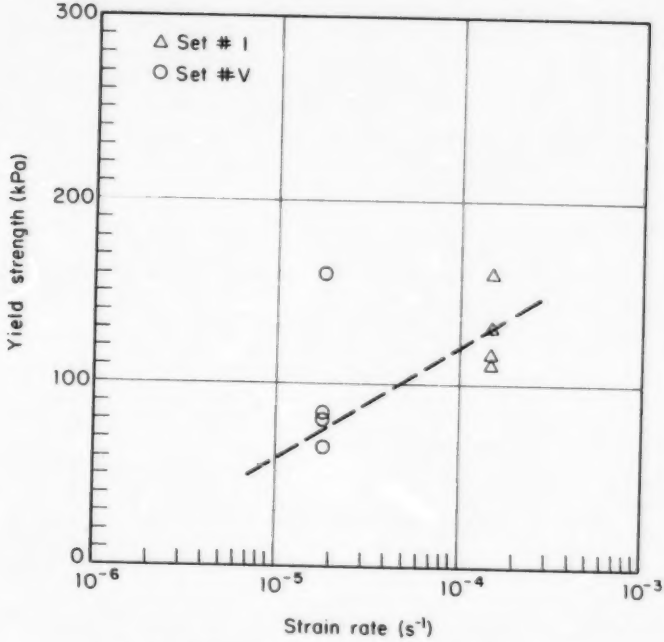

FIG. 7. Influence of Strain Rate on Yield Strength

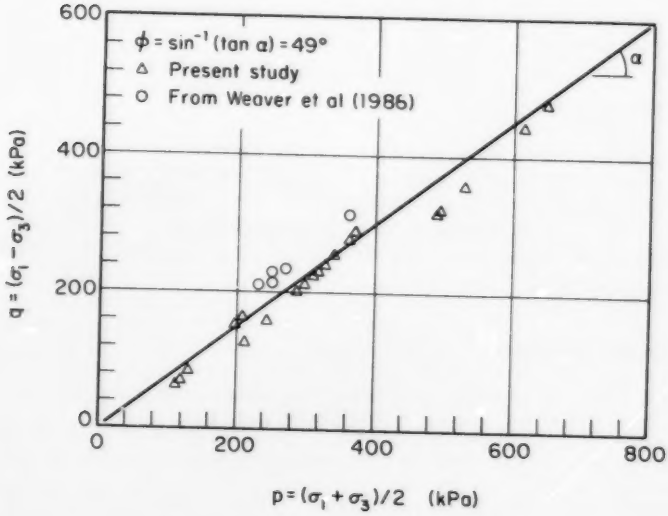

FIG. 8. Friction Properties of Spray Ice

other factors. However, the present series of tests is not adequate to separate the effects of the consolidation and shear phases since the cell confining pressure was held constant throughout each test. The influence of the confining pressure should be assessed in conducting triaxial compression tests at various confining pressures on a set of samples with the same consolidation history. This was not within the scope of the present study due to the large number of samples required.

Conclusions

The influence of the consolidation pressure and duration, shear strain rate, and temperature on the stress-strain behavior of saline spray ice has been investigated through a series of triaxial tests.

The consolidation behavior under isotropic confining pressure is consistent with previous work on similar ice materials. The existence of a yield strength envelope at rates of shear strain where creep of individual ice grains can be neglected has been shown. It is suggested that the yield strength depends on physical ice parameters (density, sample preparation), previous history factors (consolidation pressure and duration), and time-dependent effects (rate of shear strain). Strain hardening has been observed for medium and high confining pressures. The transition from hardening to softening behavior depends on consolidation time and confining pressure. That transition coincides with a change in the observed type of failure. In the -5 to 10° C range, the triaxial strain-stress plots appear to be little affected by temperature.

Comparison with previous reported tests on spray ice and broken ice shows general consistency. However, the data base is not sufficiently large to permit accurate assessment of the parameters needed for modeling. More testing is certainly required, particularly to assess the influence of the initial density and placement methods, as well as the effect of temperature, which are important in situ factors.

Acknowledgments

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